Hypersonics STEM Curriculum

Speeding Through the Atmosphere

Grade	Time	Subject Area	Key Concepts
High School	90 min	Earth and Space Science Physical Science	Atmosphere Speed/velocity

Lesson Overview

In this lesson, students will use graphical analysis to explain how temperature, density, and speed of sound vary as you move through the different layers of Earth's atmosphere. This lesson is designed to have students graph by hand, but as explained in the extension section, students can also do the graphical analysis using a program such as Excel or Google Sheets.

Prior to this lesson, students should have learned about the layers of Earth's atmosphere (troposphere, stratosphere, mesosphere, thermosphere, and exosphere). Students should also know the basics of how to create a graph (drawing, scaling, and labeling axes; creating a title; plotting points; drawing lines of best fit).

NGSS & CCSS Standards

HS-ESS1-1 Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy that eventually reaches Earth in the form of radiation.

HS-ESS2-2 Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems.

HS-PS3-2 Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative positions of particles (objects).

CCSS.MATH.CONTENT.HSN.Q.A.1 Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays

Learning Objectives

By the end of this lesson, students will be able to:

- Create a single graph displaying multiple data sets by graphing altitude vs temperature, density, and speed of sound for Earth's atmosphere.
- Analyze trends in temperature, density, and speed of sound in and across different layers of Earth's atmosphere.
- Apply their knowledge of temperature, density, and speed of sound trends across different layers of Earth's atmosphere to different contexts.

Essential/Overarching Question

How do temperature, density, and speed of sound vary as we travel through the different layers of Earth's atmosphere?

Key Vocabulary

Speed – the rate at which an object is moving. Speed is calculated by dividing the distance travelled by the time it took to travel that distance.

Speed of Sound – the rate at which sound moves through a medium. The speed of sound depends on both the density and the temperature of the medium. The speed of sound through air at 20° C (68° F) at sea level is 343 m/s (767 mph).

Atmosphere – the layer, or layers, of gas that surrounds a planet. Earth's atmosphere reaches from its surface to 10,000 km above.

Troposphere – the layer of Earth's atmosphere closest to its surface (0 – 12 km). The troposphere is the densest layer of the atmosphere and contains 99% of the Earth's water vapor. Temperature tends to decrease at altitude increases.

Stratosphere – the second layer of Earth's atmosphere (12 – 50 km). The stratosphere contains Earth's ozone layer. Temperature tends to increase as altitude increases.

Mesosphere – the third layer of Earth's atmosphere (50 – 80 km). Meteors tend to burn up in the mesosphere. The mesosphere is the coldest part of the Earth system with temperatures decreasing as altitude increases.

Thermosphere – the fourth layer of Earth's atmosphere (80 – 700 km). Temperatures increase as altitude increases.

Exosphere – the fifth and highest layer of Earth's atmosphere (700 – 10,000 km). The exosphere has a very low density and particles tend to escape into space.

Temperature – the measure of the kinetic energy of the particles in an object. A quantity to describe how hot or cold an object is.

Density – mass per unit volume. How compact an object is.

Ratio of Specific Heats – the ratio of the specific heat of a gas at constant pressure to its specific heat at constant volume. It is symbolized as γ or k.

Specific Heat – the amount of energy required to raise temperature of a unit mass of a substance.

Gas Constant – a physical constant that relates energy to temperature for one mole of a substance. R = 8.314 $\frac{J}{K*mol}$ = 1.985 $\frac{cal}{°C*mol}$. It is also known as the ideal gas constant and the universal gas constant.

Mach – the ratio of the speed of an object to the speed of sound or how many times the speed of sound an object is moving. It is often followed by a number indicating the ratio; for example: Mach 1 is the speed of sound, Mach 2 is twice the speed of sound, Mach 5 is five times the speed of sound.

Sonic – speeds equal to the speed of sound (Mach 1).

Subsonic – speeds smaller than the speed of sound (less than Mach 1).

Transonic – speeds near (Mach 0.8-1.2) the speed of sound where drag is highest (e.g. sound barrier).

Supersonic – speeds greater than the speed of sound (Mach 1 and greater).

Hypersonic – speeds greater than five times the speed of sound (Mach 5 and greater).

Sonic Boom – a loud sound associated with shock waves created by an object traveling faster than the speed of sound.

Fluid – a substance with no fixed shape; a liquid, gas, or plasma. A substance that flows when an external force is applied to it.

Flow – the motion of a fluid (liquid, gas, or plasma) when it experiences unbalanced forces.

Science Concepts Overview

Earth's atmosphere is composed of five layers: troposphere (0-12 km), stratosphere (12-50 km), mesosphere (50-80 km), thermosphere (80-700 km), and exosphere (700 – 10,000 km). Each layer has vastly different characteristics and properties. The way that temperature varies within a layer is different for each of the five layers. Temperatures tend to vary directly with altitude in the stratosphere, thermosphere, and exosphere (temperature increase with altitude) while they vary inversely in the troposphere and mesosphere (temperature decreases as altitude increases).

The density of the air follows the same trend across the entire atmosphere, as you increase altitude, the density decreases, and it does so in a non-linear manner. Density is so small in the exosphere that most particles escape into space.

Another property that varies as you move through the different layers of the atmosphere is the speed of sound. The speed of sound depends on both temperature and the ratio of specific heats. Understanding the speed of sound and how it changes at different levels of Earth's atmosphere is important for studying aircraft design, sonic booms, and can be applied to better understand the atmosphere of other planets.

Materials List

- ☐ Atmosphere Layers Pentagonal Prism (one per student)
- ☐ Speeding Through the Atmosphere handout (one per student)
- ☐ Speeding Through the Atmosphere Exit Ticket handout (one per student – there are two exit tickets per page)
- ☐ Rulers (one per student)
- ☐ Tape
- ☐ Colored pencils
- ☐ Extra graph paper

Lesson Preparation

Prior to the lesson, the instructor should make copies of the Speeding Through the Atmosphere handout and gather rulers, colored pencils, and extra graph paper for students.

If the students are going to use computers or tablets to graph the data as explained in the extensions section, the instructor should make sure that all electronic devices are charged and connected to the internet if needed.

Safety

There are no additional safety concerns beyond normal classroom procedures for this lesson.

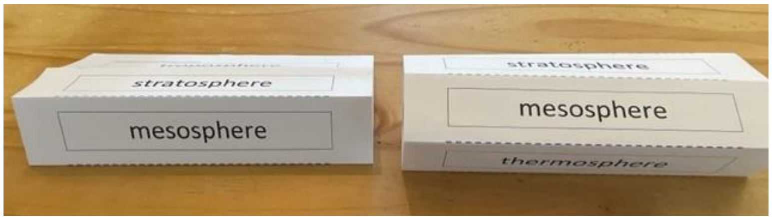
Procedure

Engage (10 minutes)

1. Prior to this lesson, students should have learned about the different layers of the atmosphere. Start class by asking students a series of questions that both review what students learned in previous lessons and to gain insight into students' understanding of the material that will be covered in this lesson:
    - Which layer of the atmosphere is closest to Earth's surface? [troposphere]
    - Which layer of the atmosphere is closest to the sun? [exosphere]
    - Which layer of the atmosphere contains the ozone layer? [stratosphere]
    - In which layer of the atmosphere to meteors tend to burn up? [mesosphere]
    - Which layer of the atmosphere has the highest temperature? [exosphere]
    - Which layer of the atmosphere has the lowest temperature? [mesosphere]

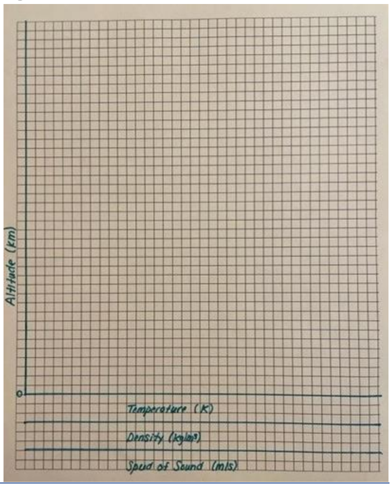
- What is a layer of the atmosphere where the temperature decreases as you increase in altitude? [troposphere, mesosphere]
- What is a layer of the atmosphere where the temperature increases as you increase in altitude? [stratosphere, thermosphere, exosphere]
- Which layer of the atmosphere is the most dense? [troposphere]
- Which layer of the atmosphere is the least dense? [exosphere]

2. Students can individually answer the questions in a variety of ways depending on the available resources such as clickers, white boards, an online application, or with the Atmosphere Layers Pentagonal Prism.
3. To use the Atmosphere Layers Pentagonal Prism:
    - Have students fold the paper backwards at the dotted line.
    - Student can us the prism in two ways. They can bring the pentagonal prism together at the top and bottom dotted lines and tape the paper to create a 3-dimensional shape. Or they can use the folds to hide other answers (see picture below).
    - Students will adjust their Atmosphere Layers Pentagonal Prism for each questions to show which layer of the atmosphere is their answer.



Explore (50 minutes)

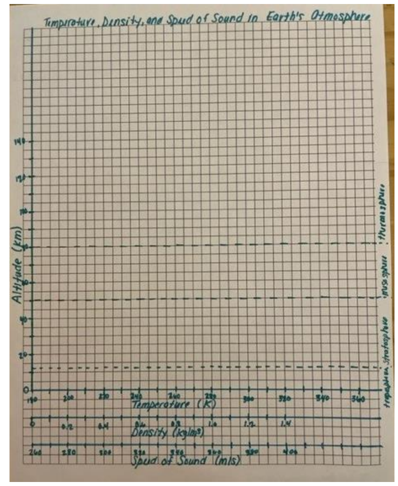
4. Have students read the introduction on the Speed Through the Atmosphere handout.
5. Students should work individually in this lesson. It is possible for students to create the graphs in a computer program (see Extension section). If that is the case, student grouping should be based on devise availability.
6. Students will explore data from the U.S. Standard Atmosphere, 1976 by creating a single graph that displays temperature, density, and speed of sound at different altitudes. The Speeding Through the Atmosphere handout gives students directions on how to create the graph:



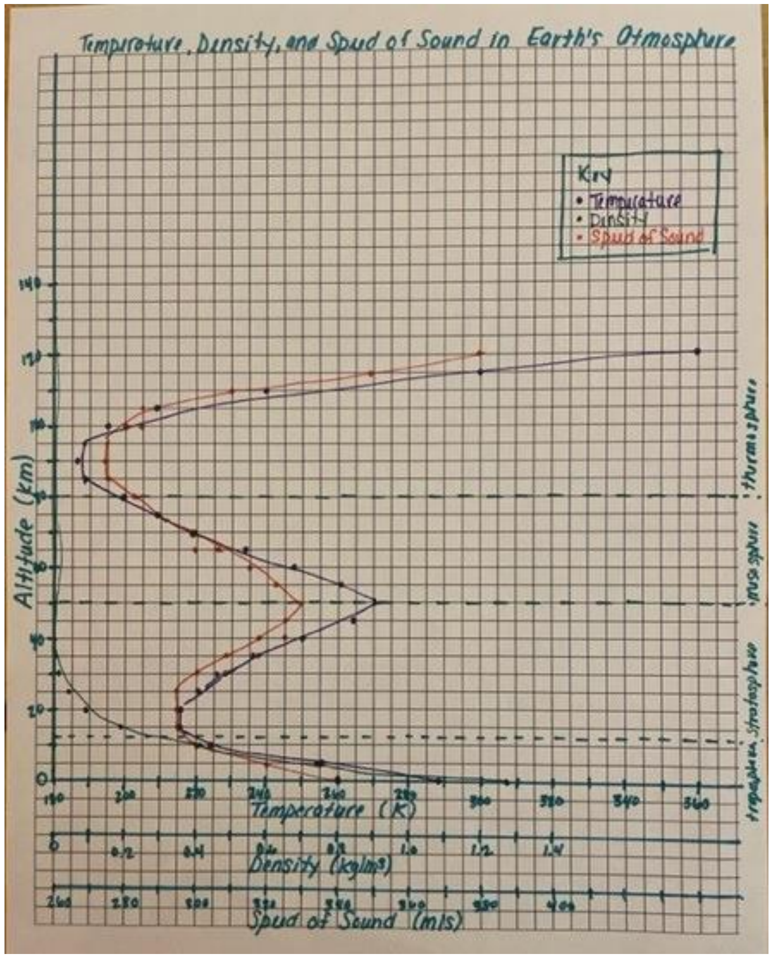
    - Use a ruler or straightedge to draw one y-axis and three stacked x- axes. Leave enough space between the three x-axes to label the scale as well as the variable name and units for each axis.
    - Look at the altitude data provided in the data table. Determine the scale you are going to use on your y-axis. Label your y-axis. Be sure to include variable name and units.
    - Look at the temperature data provided in the data table. Determine the scale you are going to

use on the temperature x-axis. Label that x-axis. Be sure to include variable name and units. (Hint: consider whether you want 0 K to be the start of your axis or not.)

- Look at the density data provided in the data table. Determine the scale you are going to use on the density x-axis. Label that x-axis. Be sure to include variable name and units. (Hint: the scales on your three x-axes do not need to be the same.)
- Look at the speed of sound data provided in the data table. Determine the scale you are going to use on that x-axis. Label that x-axis. Be sure to include variable name and units.
- Along your y-axis, label the different layers of the atmosphere (troposphere 0-12 km, stratosphere 12-50 km, mesosphere 50-80 km, thermosphere 80-700 km).



- Plot your data. It is suggested that you differentiate the different data sets by either using different colors or different point markers and create a key on the side of the graph.
- Give your graph a title.



Explain (15 minutes)

7. Students will explain their results by answering the first five Data Analysis Questions on the Speeding Through the Atmosphere handout:
    - In the table below, describe the temperature, density, and speed of sound trends as you travel higher in the different layers of Earth's atmosphere: Troposphere, Stratosphere, Mesosphere, Thermosphere*
    - *Our graph included a fraction of the data for the thermosphere as the thermosphere extends to an altitude of about 700 km. What do you think the trends for the thermosphere look like as you move closer to the sun, beyond the data we have?
    - The outermost layer of Earth's atmosphere is the exosphere (700-10,000 km). The exosphere is closest to the sun's energy, so it has very high temperatures but has very little matter as it fades into space. How do you think these effects the speed of sound in the exosphere?
    - The equation for calculating the speed of sound (c) is $c = \sqrt{\gamma RT}$ where γ is the ratio of specific heats, R is the gas constant ($286\frac{m^2}{s^2K}$), and T is temperature in Kelvin. Based on your graphs, do you think the ratio of specific heats is

constant within and across the different layers of the atmosphere? Why or why not?
- The thermosphere has extremely high temperatures, but you would not feel hot when you were in the thermosphere. Why is that?

Elaborate (10 minutes)

8. Students will elaborate on their understanding and apply their knowledge further by answering the second five Data Analysis Questions on the Speeding Through the Atmosphere handout:
    - The cruising altitude for commercial aircrafts is between 10.0 km and 12.8 km with the most common altitude being 11 km. Based on your graphs, what would be the benefit of traveling at these altitudes?
    - One of the complications of aircrafts moving at supersonic (faster than the speed of sound) and hypersonic (five times faster than the speed of sound) speeds is the creation of a sonic boom (a loud sound associated with shock waves created by an object traveling faster than the speed of sound). Our data shows that the speed of sound varies with altitude. Not all sonic booms are heard at ground level. For a sonic boom to be heard on the ground, the aircraft must travel faster than the speed of sound at ground level (343 m/s). Based on your graphs, at what altitudes can aircrafts travel at supersonic speeds (relative to the speed of sound at that altitude) without a sonic boom heard at ground level? (Hint: draw a vertical line on your graph for v = 343 m/s.)
    - The Mach number is the ratio of the objects speed to the speed of sound. Based on your graph, what is the highest Mach number an aircraft could fly at without a sonic boom being heard at ground level? What altitude(s) does that correlate with?
    - Many supersonic and hypersonic aircrafts travel through multiple layers of the atmosphere. Based on your graphs, what are things that scientists and engineers would need to take into consideration when designing these aircrafts?
    - Planetary scientists can use the speed of sound to learn more about other planet's atmospheres. How do you think they are able to do this? What data would they need to collect? What could they calculate or infer from that data?

Evaluate (5 minutes)

9. Students will complete the Speeding Through the Atmosphere Exit ticket which asks them to list:
    - Three ideas that you took away from the lesson.
    - Two wonders or questions that you have as a result of the lesson.
    - One thing you want to learn more about.

STEM Career Connections

- Atmospheric scientist
- Aerospace engineer

- Pilots
- Planetary scientist

Extensions

Rather than graphing by hand, students can do the *explore* aspect of the lesson by graphing data on a program such as Excel or Google Sheets. If you have students graph with a program, it is suggested that you provide students with a larger data set. The Public Domain Aeronautical Software provides data from the U.S. Standard Atmosphere, 1976 is different forms (https://www.pdas.com/atmos.html). Depending on the graphing ability of your class and the additional objectives of the lesson, you could provide the data to the students in a spreadsheet, or you can provide the website to the students and have them decide which data to use.

Students could further *explore* the U.S. Standard Atmosphere, 1976 data by picking another variable to graph in search of trends within and across the layers of Earth's atmosphere.

As a further *elaborate* and *evaluate*, students could create a book on the layers of the atmosphere for elementary students. They would use information they learned in this lesson combined with prior knowledge and additional research to present facts about each layer. Students could create a physical or electronic book.

References & Resources

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Atmosphere Layers Pentagonal Prism

troposphere

stratosphere

mesosphere

thermosphere

exosphere

Name: ____ Date: ____________________

Speeding Through the Atmosphere

✈ Introduction

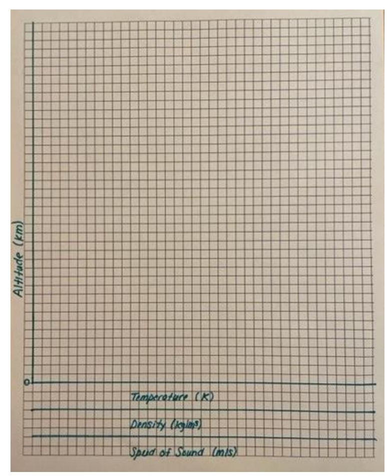
When designing an aircraft, it is important to understand the conditions that the aircraft is flying through. Different aircrafts travel through different layers of the atmospheres. Each of the layers of the atmosphere provide different flight conditions for the aircraft. And in some cases, there are large changes within the layer. Small airplanes tend to fly only in the troposphere. Commercial airplanes tend to fly near the border of the troposphere and stratosphere once they reach a cruising altitude. Sounding rockets travel between 48 km (stratosphere) and 1,200 km (exosphere) into the atmosphere collecting data for scientists. And spacecrafts must fly through all five layers of the atmosphere to enter outer space.

By the end of this lesson, you should be able to explain how temperature, air density, and speed of sound vary with altitude and apply that understanding to different flight scenarios.

✈ Graphing Instructions

You are going to create a single graph that displays multiple sets of data. In our case, the temperature, density, and speed of sound at different altitudes within Earth's atmosphere.

1. Use a ruler or straightedge to draw one y-axis and three stacked x- axes. Leave enough space between the three x-axes to label the scale as well as the variable name and units for each axis as shown in the picture.



2. Look at the altitude data provided in the data table. Determine the scale you are going to use on your y-axis. Label your y-axis. Be sure to include variable name and units.
3. Look at the temperature data provided in the data table. Determine the scale you are going to use on the temperature x-axis. Label that x-axis. Be sure to include variable name and units. (Hint: consider whether you want 0 K to be the start of your axis or not.)
4. Look at the density data provided in the data table. Determine the scale you are going to use on the density x-axis. Label that x-axis. Be sure to include variable name and units. (Hint: the scales on your three x-axes do not need to be the same.)
5. Look at the speed of sound data provided in the data table. Determine the scale you are going to use on that x-axis. Label that x-axis. Be sure to include variable name and units.
6. Along your y-axis, label the different layers of the atmosphere (troposphere 0-12 km, stratosphere 12-50 km, mesosphere 50-80 km, thermosphere 80-700 km).
7. Plot your data. It is suggested that you differentiate the different data sets by either using different colors or different point markers and create a key on the side of the graph.
8. Give your graph a title.

✈ Data

All data is from the U.S. Standard Atmosphere, 1976, provided by The Public Domain Aeronautical Software (https://www.pdas.com/atmos.html)

Altitude (km)	Temperature (K)	Density (kg/m^3)	Speed of Sound (m/s)
0	288.150	1.23	340.29
5	255.676	0.736	320.55
10	223.252	0.414	299.53
15	216.650	0.195	295.07
20	216.650	0.0889	295.07
25	221.552	0.0401	298.39
30	226.509	0.0184	301.71
35	236.513	0.00846	308.3
40	250.350	0.00400	317.19
45	264.164	0.00197	325.82
50	270.650	0.00103	329.8
55	260.771	5.68×10^{-4}	323.72
60	247.021	3.10×10^{-4}	315.07
65	233.292	1.63×10^{-4}	306.19
70	219.585	8.28×10^{-5}	297.06
75	208.399	3.99×10^{-5}	289.4
80	198.639	1.85×10^{-5}	282.54
85	188.893	8.22×10^{-6}	275.52
90	186.867	3.44×10^{-6}	274.04
95	188.418	1.39×10^{-6}	275.17
100	195.081	5.60×10^{-7}	280
105	208.835	2.33×10^{-7}	289.7
110	240.000	9.67×10^{-8}	310.56
115	300.000	4.28×10^{-8}	347.22
120	360.000	2.22×10^{-8}	380.36

✈ Data Analysis Questions

1. In the table below, describe the temperature, density, and speed of sound trends as you travel higher in the different layers of Earth's atmosphere.

	Temperature	Density	Speed of Sound
Troposphere			
Stratosphere			
Mesosphere			
Thermosphere*			

2. *Our graph included a fraction of the data for the thermosphere as the thermosphere extends to an altitude of about 700 km. What do you think the trends for the thermosphere look like as you move closer to the sun, beyond the data we have?

3. The outermost layer of Earth's atmosphere is the exosphere (700-10,000 km). The exosphere is closest to the sun's energy, so it has very high temperatures but has very little matter as it fades into space. How do you think these effects the speed of sound in the exosphere?

4. The equation for calculating the speed of sound (c) is $c = \sqrt{\gamma RT}$ where γ is the ratio of specific heats, R is the gas constant ($286\frac{m^2}{s^2 K}$), and T is temperature in Kelvin. Based on your graphs, do you think the ratio of specific heats is constant within and across the different layers of the atmosphere? Why or why not?

5. The thermosphere has extremely high temperatures, but you would not feel hot when you were in the thermosphere. Why is that?

6. The cruising altitude for commercial aircrafts is between 10.0 km and 12.8 km with the most common altitude being 11 km. Based on your graphs, what would be the benefit of traveling at these altitudes?

7. One of the complications of aircrafts moving at *supersonic* (faster than the speed of sound) and *hypersonic* (five times faster than the speed of sound) speeds is the creation of a *sonic boom* (a loud sound associated with shock waves created by an object traveling faster than the speed of sound). Our data shows that the speed of sound varies with altitude. Not all sonic booms are heard at ground level. For a sonic boom to be heard on the ground, the aircraft must travel faster than the speed of sound at ground level (343 m/s). Based on your graphs, at what altitudes can aircrafts travel at supersonic speeds (relative to the speed of sound at that altitude) without a sonic boom heard at ground level? (Hint: draw a vertical line on your graph for v = 343 m/s.)

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9. Many supersonic and hypersonic aircrafts travel through multiple layers of the atmosphere. Based on your graphs, what are things that scientists and engineers would need to take into consideration when designing these aircrafts?

10. Planetary scientists can use the speed of sound to learn more about other planet's atmospheres. How do you think they are able to do this? What data would they need to collect? What could they calculate or infer from that data?

Name: ____ Date: ____________________

Speeding Through the Atmosphere Exit Ticket

3	Three ideas that you took away from the lesson.
2	Two wonders or questions that you have as a result of the lesson.
1	One thing you want to learn more about.

Name: ____ Date: ____________________

Speeding Through the Atmosphere Exit Ticket

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